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A VIBRATING MEMBRANE ELECTROMETER WITH HIGH CONVERSION GAIN

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The concluding paragraphs of an earlier report[1] on a pressure sensor using a stretched membrane continuously vibrated at its resonant frequency mentioned the possibility of using the same design configuration to advantage in the measurement of small currents. Since interest in this application has increased in recent months, early results of work done with this type of transducer functioning as an electrometer are presented at this time.

A simplified sketch of the vibrating membrane electrometer is shown in figure 1. The membrane is driven at its resonant frequency by an electrostatic force derived from electrostatic voltages applied between the membrane and a stationary forcing plate in close proximity to one side of the membrane. If the vibrating membrane electrometer were to be used like a conventional vibrating reed electrometer, the forcing voltages would be applied between the forcing plate and the membrane while the input current lead and the output voltage lead would be connected to the detecting plate. A diagram of this method of operation is shown in figure 2. The conversion efficiency[2] for this method of operation is defined to be the ratio of the A.C. r.m.s. voltage across the capacitor to the D.C. voltage across the capacitor.

$$E'_{vm} = \frac{V'_{vm}}{V'_{si}} = \frac{\Delta C}{C} \qquad (1)$$

where $\Delta C/C$ is the ratio of the peak change in capacitance to the capacitance between the undisplaced membrane and the detecting plate. Further, since in the simplified circuit shown, the input impedance of the detecting amplifier and that of the electrometer are identical, the current conversion efficiency, E_{im}, would be identically equal to the voltage conversion efficiency. For conditions set by the cyclic stress life of the membrane, the conversion efficiency might typically be of the order of 0.10.

The vibrating membrane transducer, however, lends itself to a somewhat different method of operation which utilizes its mechanical resonant properties. The circuit diagram for this method of operation is shown in figure 3. The forcing voltage contains two components: the first a sinusoidal voltage in quadrature with the sinusoidally varying displacement of the membrane; the second, a steady voltage produced by the small current to be measured as it flows through the resistance connecting the stationary forcing plate and the transducer housing. Assuming that the transducer closely approximates a parallel plate capacitor, and that the radius of the membrane equals the radius of the forcing plate, then for small spherical displacements at the first vibrational mode of the membrane, the work done per cycle is given by the expression:

$$W_e = \frac{\pi^2 \epsilon V_{ri} V_{si} r_0^2}{X_p} \frac{\Delta C}{C} \qquad (2)$$

1. J. Dimeff, J. W. Lane, G. W. Coon, Rev. Sci. Instr. 33, 804 (1962)
2. H. Palevsky, R. K. Swank, R. Grenchik, Rev. Sci. Instr. 18, 298 (1947)

which is derived in reference 1 where all units are in the M.K.S. system and ϵ is the dielectric constant ($8.85\ 10^{-12}$ for air). V_{vi} is the variable component of the input or drive voltage. V_{si} is the steady component of the input voltage. r_o is the radius of the membrane and Xp is the spacing between the undisplaced membrane and the stationary plates.

This energy is approximately equal to the energy stored in the membrane at peak displacement divided by the Q of the system, multiplied by 2π.

$$W_e = 2\pi \frac{W_{max}}{Q} \tag{3}$$

If K is defined as the spring constant of the system then

$$W_e = \frac{1}{2} \frac{K a_o^2}{Q} (2\pi) \tag{4}$$

where a_o is the maximum average displacement of the membrane. Now since $\Delta C/C = a_o/X_p$ and $K = 8\pi T$ where T is the tension per unit length of circumference, the following relationship is obtained from equation (4).

$$W_e = \frac{8\pi^2 T}{Q} X_p^2 \left(\frac{\Delta C}{C}\right)^2 \tag{5}$$

From equations (2) and (5) it follows that

$$V_{si} = \frac{8 T X_p^3}{\epsilon V_{vi} r_o^2 Q} \frac{\Delta C}{C} \tag{6}$$

The capacitance change, ΔC, due to the displacement of the membrane can be measured by impressing a steady voltage, Vo, between the membrane and the detecting plate. If one assumes small amplitude spherical deformations and assumes further that the diameters of the membrane and detecting plate are equal, and that the flow of charge to the detecting device is negligible, then the following equation may be written for the displacement induced voltage

$$V_{vm} = \frac{\Delta C}{C} V_o \tag{7}$$

The conversion gain of the transducer is defined as the ratio of the peak A.C. output voltage to the D.C. input voltage.

$$E_{vm} = \frac{V_{vm}}{V_{si}} \tag{8}$$

From equations (6) and (7) the following expression is obtained for the conversion gain:

$$E_{vm} = \frac{\epsilon Q V_o V_{vi} r_o^2}{8 T X_p^3} \qquad (9)$$

or since $f = \frac{.382}{r_o}\sqrt{\frac{T}{\sigma}}$ where f is the resonant frequency of the membrane and σ is its mass per unit area

$$E_{vm} \approx \frac{\epsilon V_o V_{vi}}{55 \sigma X_p^3} \frac{Q}{f^2} \qquad (10)$$

Pressure transducers of the vibrating membrane type have been constructed with the following approximate mechanical and electrical characteristics:

σ = 0.02 Kilograms/Met.^{2}
X_p = 3.85×10^{-5} Met.
f = 5000 cycles/sec.
$Q = 3 \times 10^4$

If it is assumed further that Vo = 200 volts and V_{vi} = 50 volts then

$$E_{vm} \approx 1.4 \times 10^3$$

This number, then, gives an effective voltage conversion gain for the vibrating membrane electrometer used in the method described above. The current conversion gain can be obtained by simple substitution of the current-resistance product for the input and output voltages.

$$\frac{V_{vm}}{V_{si}} = \frac{I_{vm}}{I_{si}} \frac{R_{vm}}{R_{si}} \approx 1.4 \times 10^3$$

substituting values of Rvm = 5×10^6 ohms and Rsi = 5×10^{15} ohms, the following value is obtained for the current conversion gain

$$E_{Im} \approx 1.4 \times 10^{12}$$

The relatively high values obtained for the conversion gain are the result of several factors incorporated in the design:

a. The electrometer input is used only to produce a component of force.

b. The magnitude of the force is multiplied by a sinusoidally varying voltage of large amplitude.

c. The force is integrated over a long period of time by operating at the resonant frequency of a membrane with small internal losses.

d. The nearly perfect shielding between the two halves of the transducer allows application of high voltages to the detecting side and provides, thereby, a direct increase in the magnitude of the output signal which is proportional to the displacement of the membrane and the bias voltage.

e. The output current from the transducer is allowed to flow through a much smaller resistance than the input resistance thus allowing a further increase in the measured current.

In general, most types of electrometers discussed in the literature may be divided into three broad catagories; mechanical electrometers, vacuum tube electrometers, and dynamic capacitor electrometers. The vibrating membrane electrometer belongs to both the mechanical and dynamic capacitor catagories. In all of the above classes of electrometer circuits, the critical element is the transducer, and if one compares the efficiencies of transducers which are currently in use in electrometer circuits, it is apparent that the vibrating membrane transducer represents a considerable improvement. For example: The Hoffman Electrometer[3] has an energy conversion efficiency of ; The dynamic capacitor in reference 2 has a conversion efficiency of 0.20; A typical gain for a vacuum tube electrometer is unity. The conversion gain of the vibrating membrane electrometer is greater than 1000 .

Only one model of the vibrating membrane electrometer has been constructed to date and the results of testing performed with this instrument were very encouraging. A photographic view of the high impedance input half of this electrometer is shown in figure 4. This electrometer had an input impedance greater than 10^{16} ohms and a sensitivity of one millivolt. The vibrating membrane electrometer has many of the problems inherent to the vibrating reed electrometer such as zero drift due to change in contact potential and charge accumulation on the insulators due to mechanical stress, and background currents due to alpha particle emission. These problems were not investigated in the preliminary tests which have been performed. However it is believed that if the current state of the art could be achieved in these problem areas the advantages of this type of instrument would be manifest. It is small and rugged which makes it appealing for aerospace applications. It should be capable of measuring currents smaller than 10^{-17} amperes, and it does not suffer from many of the limitations inherent to vacuum tube electrometers. It has a higher conversion gain than any of the electrometers currently being used.

3. B. Zipprich, Physik Zeits. 37, 35 (1936)

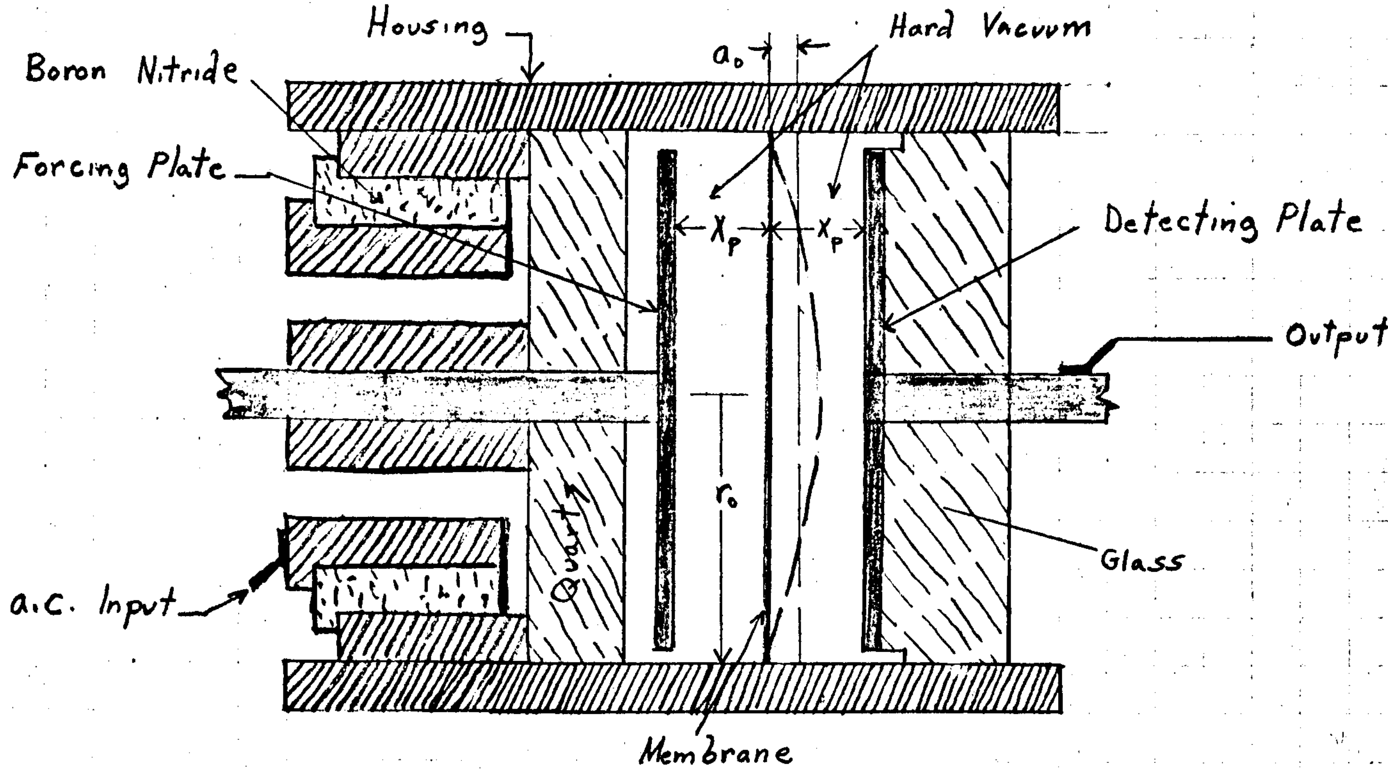

Fig. 1. Simplified Sketch of the Vibrating Membrane Electrometer.

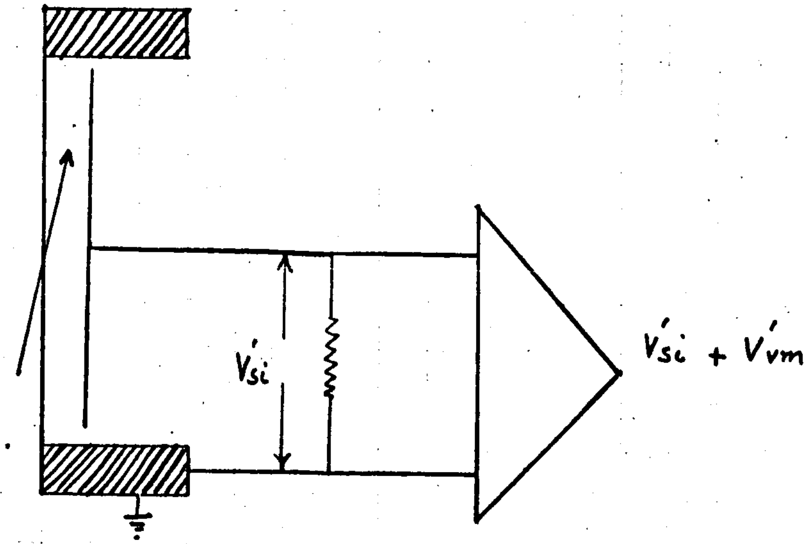

Fig. 2. Conventional Operation of a Dynamic Capacitor Electrometer

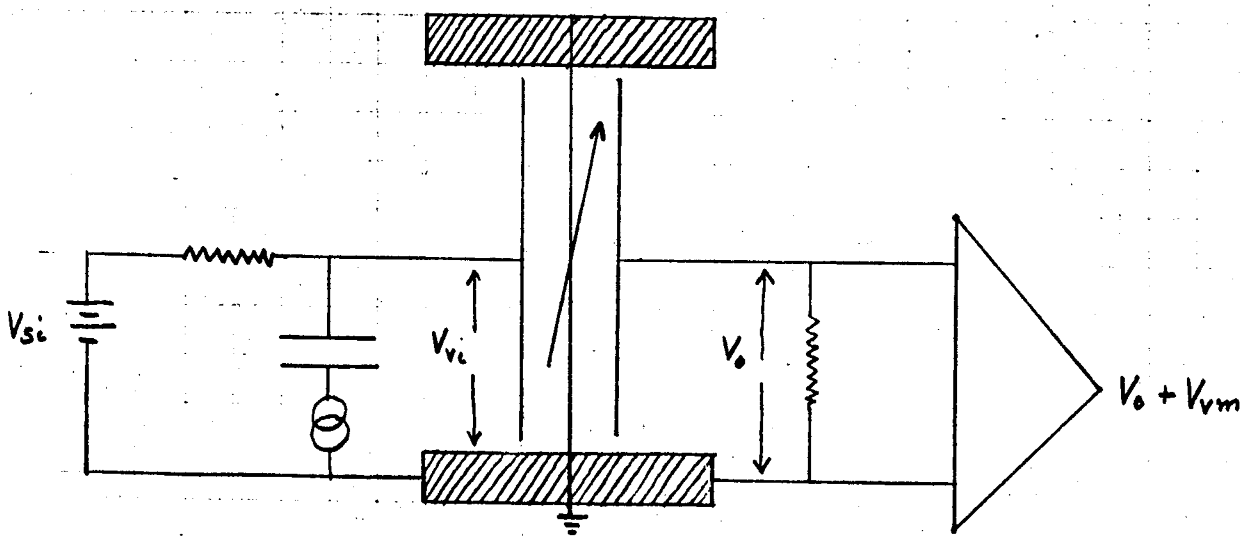

Fig 3. High Conversion Gain Vibrating Membrane Electrometer

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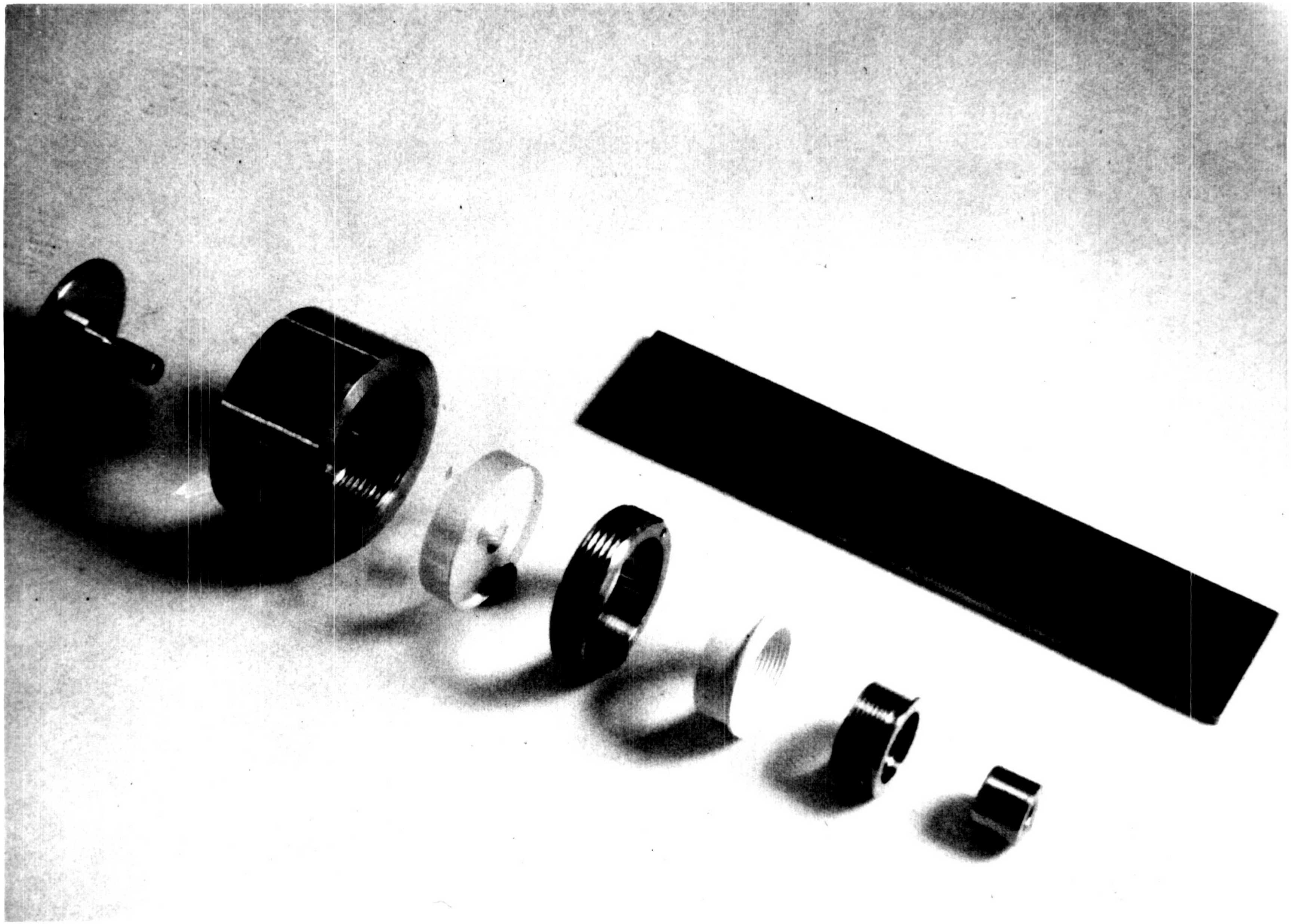

Figure 4